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Aircraft Structures Technical Memorandum 519

THERMOELASTIC RESPONSE OF AN EPOXY (U)

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THERMOELASTIC RESPONSE OF AN EPOXY (U)

by

R.W. Eustace

SUMMARY

An investigation has been conducted into the thermoelastic response of an Epoxy subjected to a cyclic compressive loading. A SPATE 8000 detector is used to monitor the response as the mean stress, frequency and cyclic amplitude are varied individually. The response is briefly discussed with respect to the theoretical equation predicting the behaviour of an isotropic Hookean material, and a measure of the Epoxy's mean stress dependence of the thermoelastic parameter is given.

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TABLE OF CONTENTS

1 INTRODUCTION

SPATE 8000 is a device which measures the thermoelastic response of a material under a cyclic (adiabatic) load. The thermoelastic response of a material arises due to a coupling between mechanical deformation and the change in thermal energy of an elastic material. The first theoretical treatment of this phenomenon is attributed to Lord Kelvin [1], and the resulting law states that the rate of change in temperature of a dynamically loaded body is directly related to the rate of change of the principal stress sum under adiabatic conditions. By the application of this law the SPATE system has successfully been used for measuring dynamic stresses in many engineering components [2], [3].

As composite materials are becoming widely used, an understanding of their thermoelastic behaviour is sought. This paper deals with an investigation into the behaviour of an epoxy material, one of the components of a composite.

A specimen of Araldite MY720 was subjected to a compressive cyclic stress S, consisting of a mean stress component S_m and a cyclic stress amplitude of S_a at a frequency of ω, and three different tests were conducted whilst the thermoelastic response was monitored using the SPATE detector. The first test involved determining the effect of varying the mean stress, whilst keeping the cyclic amplitude and frequency constant. The second test was to alter only the frequency; whilst the third involved only varying the cyclic stress amplitude.

2 THEORY

When a material is subjected to a cyclic stress of the form

$$S = S_m + S_a \sin \omega t, \tag{1}$$

Kelvin's Law [1] predicts that the thermoelastic response will be given by

$$\Delta T = -K_o T_o \Delta S \tag{2}$$

where ΔT is the change in temperature

T_o is the mean temperature
ΔS is the change in S, the sum of the principal stresses, and
$K_o = \alpha/\rho_o C_\epsilon$ is the thermoelastic constant.
where α is the coefficient of linear thermal expansion
ρ_o is the unstrained density, and
C_ϵ is the specific heat at constant deformation

However it has been subsequently proved [4], that the thermoelastic constant is mean stress dependent, and given by

$$K = (\alpha - \frac{1}{E^2}\frac{\partial E}{\partial T}S_m)(\rho_o C_\epsilon)^{-1} \tag{3}$$

The thermoelastic parameter can be seen to be stress dependent due to the temperature dependence of E, the modulus of elasticity. Thus the true thermoelastic response due to a cyclic stress, in the form of eqn(1), is given by

$$\rho_o C_\epsilon \frac{T - T_o}{T_o} = -(\alpha - \frac{1}{E^2}\frac{\partial E}{\partial T}S_m)S_a \sin\omega t + \frac{1}{4E^2}\frac{\partial E}{\partial T}(S_a)^2(1 - \cos 2\omega t) \tag{4}$$

As can be seen, the response contains two components, one at the frequency of loading, as well as another at twice the frequency. The fundamental frequency component can be seen to contain two terms, the first as predicted by Lord Kelvin and proportional to α, while the second (although typically only a few percent of the first term) is proportional to S_m, the mean stress. The negative sign in front of this fundamental component indicates a phase change of 180° between this component and T. Thus a stress increasing in the positive direction causes a decreasing temperature. Since, for almost all materials, $\partial E/\partial T$ is negative, the second term is of the same sign as the first, and hence an increase in S_m increases the size of the temperature amplitude, and thus the thermoelastic effect. The second component, at 2ω, (typically less than 4% of the fundamental component [5]) is only dependent on S_a, as well as material properties.

This non-linear thermoelastic response of eqn(4) has been verified by experiment [5], [6], and this detailed knowledge of the response of metallic materials allows a better understanding of the stresses which exist in them by measuring the thermoelastic response. It also leads to a way of allowing residual stresses to be measured [7].

This paper investigates the thermoelastic response of the epoxy Araldite MY720, in order to determine whether eqn(4) also governs their behaviour. Only the fundamental frequency component is considered.

3 EXPERIMENT

The epoxy is a mixture of 100 parts of MY720 hardened with 30 parts by weight of DiaminoDiphenylSulphone (DDS) and is a brittle light brown transparent material. The manufactures, CIBA-GEIGY, claim *'exceptionally good long term high temperature performance, high mechanical strength, and outstanding heat resistance'* [8]. The MY720 was chosen because it resembles the epoxy component of the Hercules pre-pregnated tape AS4/3501-6, used in aircraft such as the F/A-18. The epoxy was cured at $\leq$ 125°C for 12 hours, then post-cured at 150°C for two hours, and 170°C for a further two hours. The specimen tested had a cross-sectional area of 28mm $\times$ 23mm and was approximately 50mm long, and was mounted vertically with its smallest face between two flat plates and compressed with a cyclic load in a $\pm$ 50 kN MTS uniaxial testing machine.

Before any measurements were taken a SPATE scan of the front face of the specimen was executed to confirm that the specimen was not subject to bending, but in a state of uniform stress. The SPATE detector's view was then centred on the middle of the specimen, and the uncorrelated detector signal was taken from the back of the SPATE Brookdeal correlator. Whilst the correlator unit is designed to filter out any signal apart from the fundamental frequency, by taking the output of the detector from a series connection on the detector circuitry at the rear of the correlator unit, the uncorrelated signal can be processed externally, and hence any harmonics detected. Thus only the SPATE detector is utilized in the experiment, and not the Brookdeal correlator unit, as in normal use of the equipment.

The uncorrelated SPATE signal, and a load cell signal, were then both passed through a 50 Hz low pass filter, before being processed by a Wavetek 804A FFT analyser. This was used to determine the frequency spectrum of both input signals, as well as the transfer function between them, in order to normalise the SPATE detector signal with respect to the load. It also measured the phase difference between both signals.

The SPATE detector signal is proportional to the infra-red flux from the specimen, and thus varies directly with the temperature and load. This was monitored via a signal from a load cell. The frequency spectrum thus gives the rms values of these signals, which are proportional to their respective cyclic amplitudes.

3.1 Variation of Mean Stress

The mean stress was varied in three different tests: for the first it was varied from -6.8 MPa to -31.2 MPa, with a cyclic stress amplitude S_a of 5.4 MPa and a loading frequency of 5 Hz; the second test as for the first, but at a frequency of 1 Hz; whilst the third test was from -6.1 MPa to -33.4 MPa, for a fixed frequency of 1 Hz at a stress amplitude of 3.1 MPa.

Figure 1 shows these results. Whilst the load should remain constant, as the mean stress was varied, small variations less than 1% did occur, and so the rms value of the SPATE signal was divided by the rms load signal to remove these variations. Thus Fig. 1 is essentially a plot of the normalised SPATE detector response vs mean stress. The actual data points are shown plotted, with a line of best fit through each set of points.

3.2 Frequency Response

The frequency was varied from 1 Hz to 30 Hz, in both directions, with a mean compressive load of 15.5 MPa, and a cyclic stress amplitude of 5.7 MPa. The filter was not included in the set-up for this test.

Figure 2a shows the normalised rms SPATE detector amplitude response vs frequency. As the frequency was changed the input to the load system was corrected such that the cyclic stress amplitude remained at its initial value. However, to remove any small variations that may have occurred, the SPATE signal was normalized with respect to the load. Hence Fig. 2a is also essentially a plot of the normalised SPATE signal vs frequency. Figure 2b shows the phase difference, between the sinusoidal SPATE and load cell signals, plotted against frequency.

3.3 Variation of Cyclic Stress Amplitude

This test was done in two parts. For the first the cyclic stress amplitude S_a was changed, in steps of 0.4 MPa, between a maximum of 11.7 MPa to 1.5 MPa , in both directions, for a frequency of 10 Hz, and a mean compressive stress of 15.5 MPa. The second part involved changing the cyclic stress amplitude from 3.9 MPa to 11.7 MPa in a single step, with a mean compressive stress of 15.5 MPa and at a frequency of 20 Hz. The filter was not utilized for the second part of the test.

The experimental set-up for the second part also involved monitoring the temperature of the epoxy sample. Two copper-constantan thermocouples were attached to the specimen, one embedded in the centre of the test piece while the other was attached to the surface. The signals from these were calibrated by a Doric 235 Processor, which displayed the temperatures on a digital monitor.

Figure 3a shows the effect of variation of cyclic amplitude on the SPATE detector output. As the cyclic stress amplitude is increased, it is expected from eqn(4) that the detector response will increase proportionately. Thus by plotting the rms SPATE signal normalized by the rms load signal, the resulting graph should be a horizontal line. Figure 3b shows the specimen temperature response for the step change in cyclic amplitude.

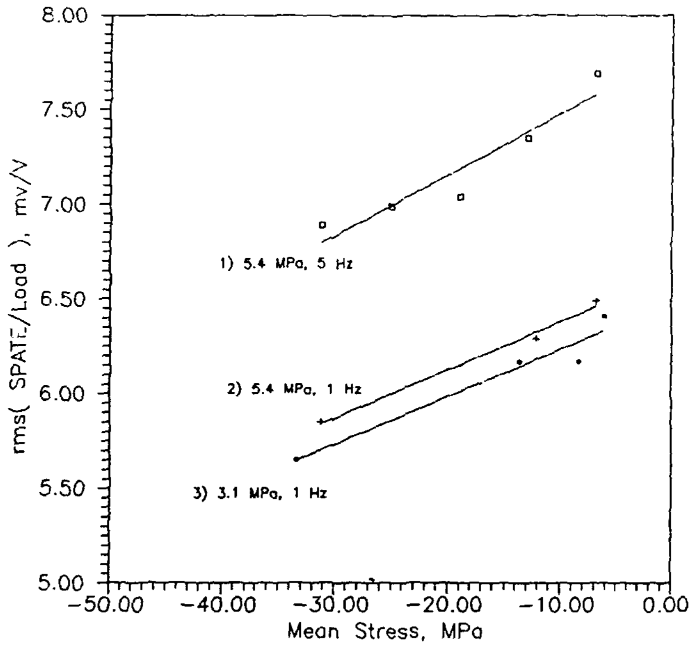

Figure 1 SPATE signal amplitude response with variation of mean stress.

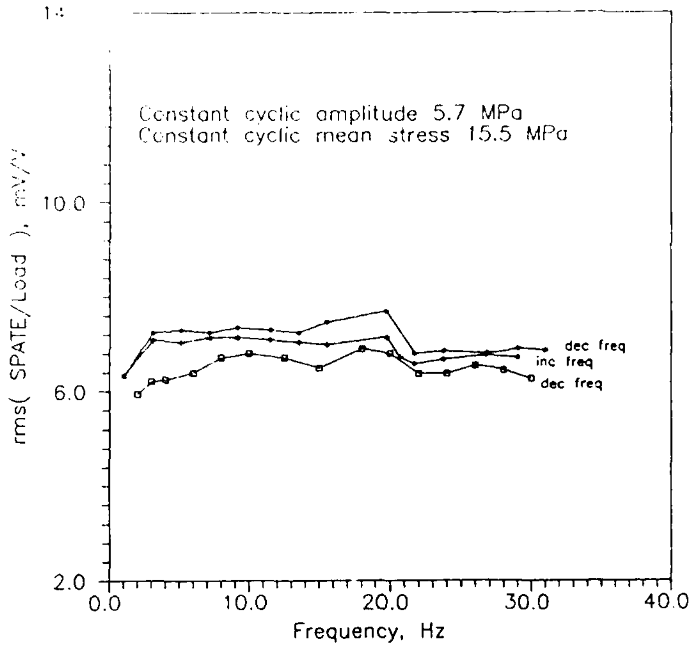

Figure 2a SPATE signal amplitude response with variation of cyclic frequency.

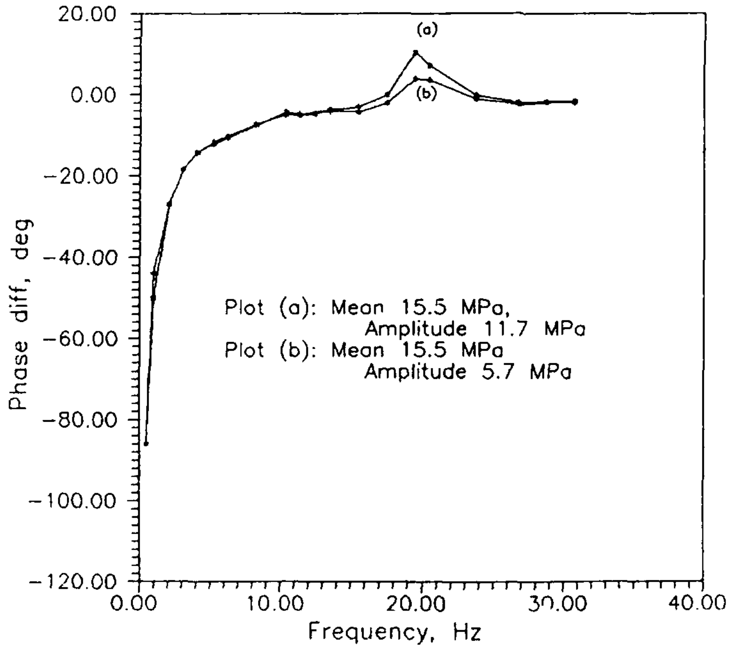

Figure 2b Signal phase difference with variation of cyclic frequency.

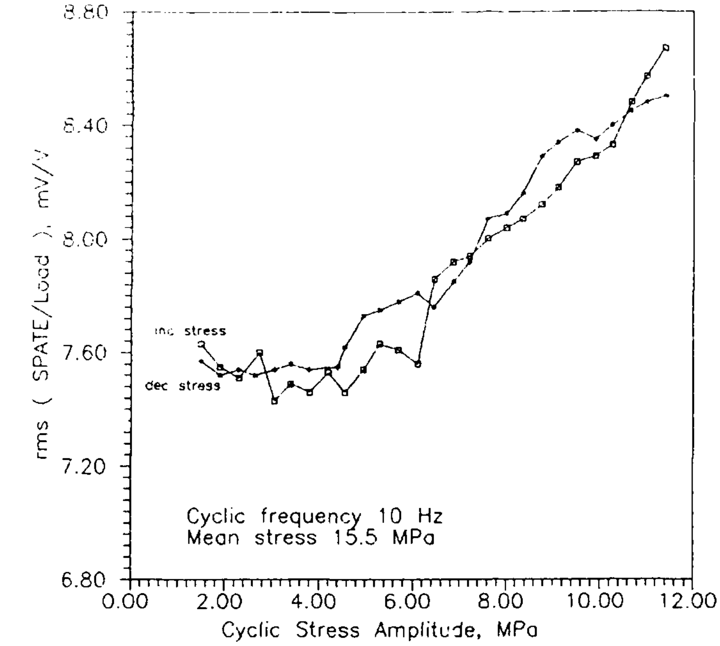

Figure 3a SPATE signal amplitude response with variation of cyclic stress amplitude.

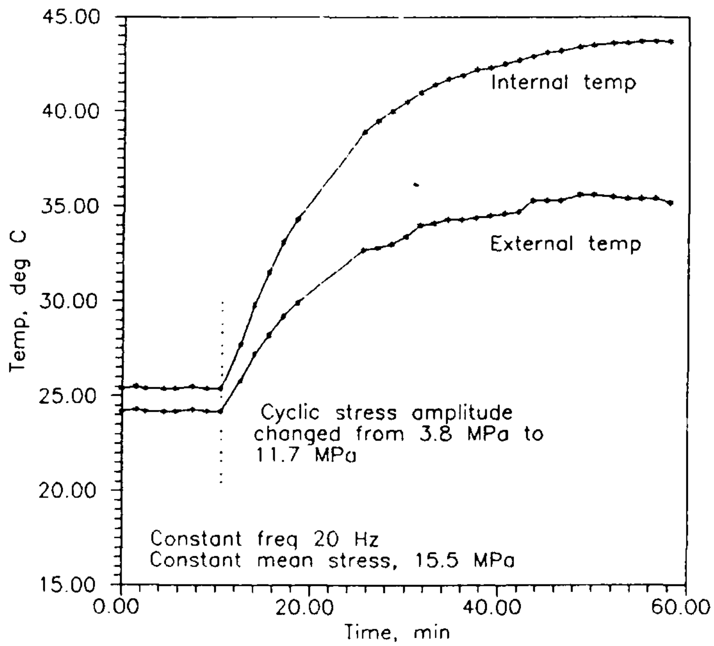

Figure 3b Specimen temperature response with a large change in cyclic amplitude.

4 DISCUSSION

Many difficulties were encountered in measuring the signal from the SPATE infra-red detector. It was discovered, for instance, that if the load cell signal remained connected to the Brookdeal unit, as in the normal operation of SPATE, then the uncorrelated SPATE signal taken from the Brookdeal unit was affected by the load cell signal. Whilst this interference was not large enough to affect the normal operation of SPATE, it was detectable when the uncorrelated signal was externally analysed. By utilizing the connection at the rear of the correlator unit, and not connecting a load cell signal to it, this problem was avoided.

The background noise level was also having an effect on the signal. The SPATE signal contained a low signal to noise ratio, and this made it difficult to select a suitable range for the A-D convertor of the Wavetek, whilst still maintaining high resolution. In order to improve this the low pass filter was included, to remove the high frequency noise, and so allow the A-D signal range to be closer to the actual signal range at the frequency of interest.

4.1 Variation of Mean Stress

Figure 1 shows that as the mean stress is increased in the tensile direction, the fundamental frequency component of the SPATE signal increases. Thus the epoxy behaves as predicted by eqn(4), for a material with a negative value of $\partial E/\partial T$.

A normalised measure of the variation of K with respect to the mean stress may be written as

$$\frac{1}{K_o}\frac{\partial K}{\partial S_m} = -\frac{1}{\alpha E^2}\frac{\partial E}{\partial T}, \tag{5}$$

and values obtained from Fig. 3 are shown below.

Plot	S_a (MPa)	ω (Hz)	$\frac{1}{K_o}\frac{\partial K}{\partial S_m}$ (MPa^{-1})
1	5.4	5	4.1×10^{-3}
2	5.4	1	3.9×10^{-3}
3	3.1	1	3.8×10^{-3}

The difference in these values is within experimental error.

4.2 Frequency Response

As can be seen in Fig. 2a, the SPATE signal amplitude response only drops away at the low frequencies where adiabatic conditions no longer apply, otherwise the signal is essentially independent of frequency, except for a drop at around 20 Hz. This is matched by a peak in the phase difference between the SPATE and load cell signals, at this frequency.

Equation(4) predicts no relationship between amplitude and frequency, or phase difference and frequency, and thus this behaviour at 20 Hz is not explained. It is not expected to be caused by a resonant frequency of the test piece, since this behaviour has been noticed before in other composite specimens.

4.3 Variation of Cyclic Amplitude

Had the SPATE signal obeyed eqn(4), then Fig. 3a would have been a horizontal line. However, as can be seen, the response is non-linear. As the cyclic amplitude increased from 2.5 MPa to 10 MPa, had the SPATE signal also increased four times, the ratio of signals would have remained at 7.6 mV/V, but as can be seen the ratio of signals increased to 8.0 mV/V.

Figure 3b shows the temperature response of the specimen to a change in cyclic stress amplitude. With the high cyclic stress amplitude the surface temperature is approximately 15°C hotter than at the lower stress amplitude, and there is also a larger temperature difference between the inside and outside of the specimen. A surface temperature change of this magnitude causes a shift of the black body radiation level vs wavelength graph, and, as SPATE doesn't contain a filter, this may cause a substantial change in detector response. This irreversible heat generation, causing an increase in T_o, a larger internal-external temperature difference, and a shift in wavelength of the black body curve makes interpretation of Fig. 3a difficult.

The correlated SPATE signal was also recorded as the cyclic stress range was changed in large steps. At frequencies of 5, 10 and 20 Hz, the signal changed to a new level immediately the cyclic stress amplitude was altered, but then continued to drift steadily in the same direction as it slowly reached a new equilibrium. The immediate response would be expected, since the thermoelastic signal will increase immediately the cyclic amplitude is increased, whilst the slow continuation of signal change may well be due to the increase of the mean temperature of the specimen. However, it may also be due to a gradual change in stress caused by a variation of E as T_o varies. This gradual approach of the SPATE signal to a new value was recorded at 5, 10, and 20 Hz, but was not seen at 1 Hz.

5 Conclusion

Results show that the SPATE detector response

- increases as the mean stress increases in a positive direction, and so behaves similar to metals, and has an approximate value of

$$\frac{1}{K_o}\frac{\partial K}{\partial S_m} = 3.9 \times 10^{-3} \quad MPa^{-1}$$

- appears basically independent of frequency for the range tested (3 to 30 Hz),
- is non-linear with increasing cyclic stress amplitude, accompanied by an increase in specimen temperature T_o, due to some form of irreversible heating.

Theories can now be formulated about the trends shown here, and varified by more refined and specific tests. It is possible that some of these observations may be accounted for by including the stress-temperature-moisture interaction effects outlined in [9].

Acknowledgments The author would like to thank J.G. Sparrow and S.A. Dunn for their assistance and advice.

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16. ABSTRACT
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